

Propulsion Control and Health Management (PCHM) Technology for Flight Test on the C-17 T-1 Aircraft

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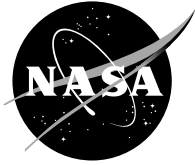
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ABSTRACT

The C-17 T-1 Globemaster III is an Air Force flight research vehicle located at Edwards Air Force Base. NASA Dryden and the C-17 System Program Office have entered into a Memorandum of Agreement to permit NASA the use of the C-17 T-1 to conduct flight research on a mutually coordinated schedule. The C-17 Propulsion Control and Health Management (PCHM) Working Group was formed in order to foster discussion and coordinate planning amongst the various government agencies conducting PCHM research with a potential need for flight testing, and to communicate to the PCHM community the capabilities of the C-17 T-1 aircraft to support such flight testing. This paper documents the output of this Working Group, including a summary of the candidate PCHM technologies identified and their associated benefits relative to NASA goals and objectives.

NOMENCLATURE

ARC	Ames Research Center
CEDU	Comprehensive Engine Diagnostic Unit
DFRC	Dryden Flight Research Center
DoD	Department of Defense
EDMS	Engine Distress Monitoring System
EGT	Exhaust Gas Temperature
eSTORM	Enhanced Self-Tuning On-board Real-time Model
FAA	Federal Aviation Administration
FADEC	Full-Authority Digital Engine Control

FOD	Foreign Object Damage
GRC	Glenn Research Center
HOTProbe	High Operating Temperature Probe
IDMS	Inlet Debris Monitoring System
IFCS	Intelligent Flight Control System
ISTAR	Integrated System Test of an Air-breathing Rocket
LEC	Life Extending Control
LIGA	Lithography Electroplating Molding
MEMS	Microelectromechanical systems
NASA	National Aeronautics and Space Administration
OCM	Oil Condition Monitor
ODM	Oil Debris Monitor
PC	Propulsion Control
PCHM	Propulsion Control and Health Management
PHM	Propulsion Health Management
POC	Point of Contact
RBCC	Rocket-Based Combined Cycle
RD Server	Remote Diagnostics Server
REFLCS	Research Flight Computing Systems
SBIR	Small Business Innovation Research
SiC	Silicon Carbide
SOA	State-of-the-Art
SOI	Silicon On Insulator
SPO	System Program Office
SWAN	Stress Wave Analysis
TBD	To Be Determined
TEAMS RT	Testability Engineering And Maintenance System – Real-Time
TRL	Technology Readiness Level
UAV	Unmanned Air Vehicle
USAF	United States Air Force

INTRODUCTION

Propulsion Control and Health Management (PCHM) is recognized as a vital technology for enhancing the performance, operability, safety, and reliability of aircraft propulsion systems. As such, there are numerous PCHM research activities ongoing within NASA, other government agencies, and industry. However, in order for these efforts to ultimately transition from research activities into technologies accepted and incorporated into industry products, they must be properly matured and demonstrated. Flight testing is a key step in this development process. The Air Force C-17 T-1 aircraft, located at Edwards Air Force Base, is viewed as an ideal test-bed vehicle on which to flight demonstrate many PCHM technologies. In order to identify and facilitate the maturation of ongoing PCHM research technologies that would benefit from flight testing on the C-17 T-1 aircraft, a C-17 PCHM Working Group was established. This group included NASA, Department of Defense, FAA, and industry representatives. This document

summarizes the C-17 PCHM Working Group charter and membership, the candidate technologies identified for potential future flight testing on the C-17 T-1 aircraft, the associated benefits of these technologies relative to NASA goals, and the capabilities of the C-17 T-1 aircraft to host these flight test experiments.

C-17 PROPULSION CONTROL AND HEALTH MANAGEMENT WORKING GROUP

The C-17 Propulsion Control and Health Management Working Group was formed in order to foster discussion and coordinate planning amongst the various government agencies conducting PCHM research with a potential need for flight testing. This ad hoc group was formed in early 2002. Coordination amongst this group took place through telecons, emails, and a C-17 PCHM Workshop which was held in Cleveland, Ohio July 11-12th, 2002. The vision of this group was to develop an integrated approach to:

- Mature and validate propulsion control and health management technologies that contribute to the NASA agency goal to enable a safer, more secure, efficient, and environmentally friendly air transportation system
 - Emphasize technologies that benefit commercial and military aircraft
 - Leverage and integrate technologies being developed in other efforts
 - Mature technologies from low Technology Readiness Levels (TRL's) of (2-4) to TRL's of 5-6 to reduce the risk for industry acceptance. (A definition of NASA TRL's is included in Appendix A.)

As part of achieving this vision, the working group set the following objectives:

- Communicate to the PCHM Community the availability and capability of C-17 T-1 as a flight test-bed
- Understand what PCHM technologies are being developed across government agencies (NASA, DoD, FAA) that will be ready for flight testing in government fiscal years 2003-2007
- Establish a short list and preliminary roadmap for flight test of PCHM technologies on C-17 T-1
- Develop an initial plan for the next steps in the roadmap development and implementation process
 - Establish communication with the principal investigators associated with technologies suitable for flight test. Keep abreast of technology development and help advocate for technology maturation for flight test
 - Identify the required modifications to the C-17 T-1 in order to develop it into a test-bed for PCHM technologies

The working group included the following government planning committee members and industry advisory committee members:

Planning Committee Members

Jon Dell	Air Force Research Laboratory
Bill Emmerling	FAA Technical Center
Fred Engle	USAF, C-17 SPO
Sanjay Garg	NASA Glenn Research Center
Jerry Henry	NASA Dryden Flight Research Center
Ed Huff	NASA Ames Research Center
Trindel Maine	NASA Dryden Flight Research Center
John Orme	NASA Dryden Flight Research Center
Ann Patterson-Hine	NASA Ames Research Center
Juan D. Satterfield	USAF, F117 Propulsion SPO
Ken Semega	Air Force Research Laboratory
Don Simon	Army Research Laboratory, Vehicle Technology Directorate
Capt Ben Spencer	USAF, C-17 SPO
Keith Schweikhard	NASA Dryden Flight Research Center
Mike Venti	Analytical Services and Materials, Inc. (NASA Dryden)
Jim Zakrajsek	NASA Glenn Research Center

Advisory Committee Members

Doug Stetson	Pratt & Whitney
Bruce Wood	Pratt & Whitney

The working group concluded its activities with the documentation of the candidate PCHM technologies for flight test, and dissemination of this information to NASA management.

PCHM TECHNOLOGY FOR FLIGHT TESTING

For the purpose of this document, Propulsion Control and Health Management (PCHM) is defined to include various technologies spanning the areas of sensors, diagnostic and prognostic algorithms, controls, and integrated controls and diagnostics. Collectively, these technology areas make up the framework of a propulsion control and health management system as shown in Figure 1. A summary of these areas along with a discussion of the candidate technologies from each is provided below (with the exception of actuators as no actuator technology was identified for flight test by the C-17 PCHM Working Group). A notional C-17 PCHM technology roadmap for flight test is presented later in the paper. More detailed information on each individual technology can be found in Appendix B including: 1) a point of contact; 2) a technology description; 3) justification for flight test; 4) current schedule and technology readiness level; 5) estimated schedule and resources to support flight testing; 6) flight test-bed requirements; and 7) success criteria for flight testing.

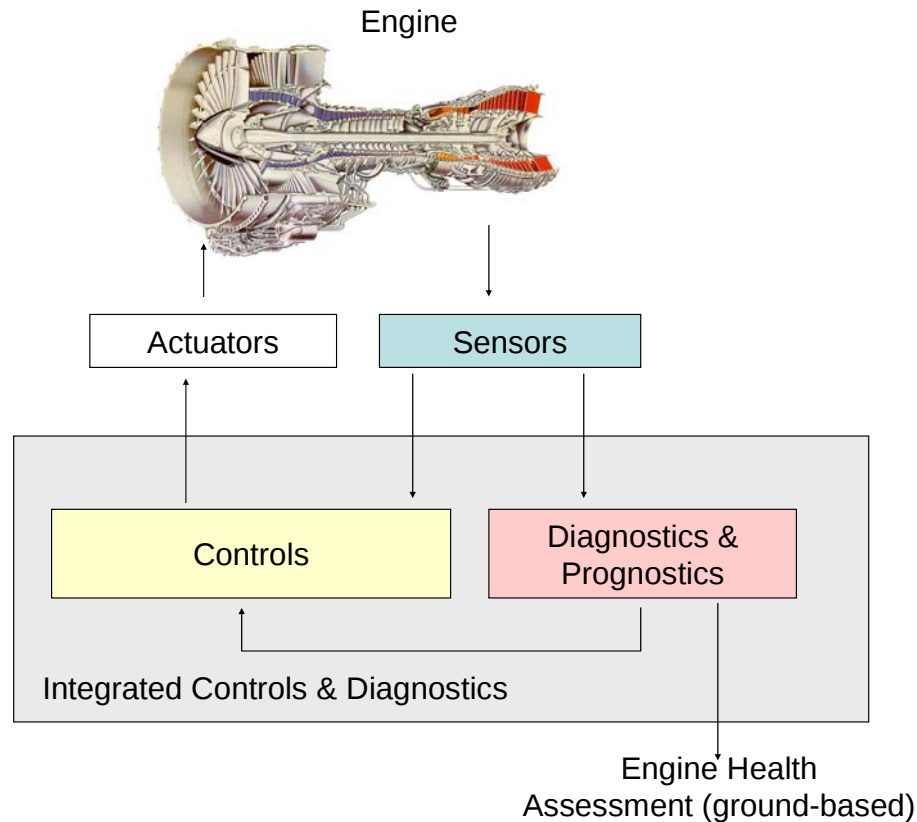


Figure 1. Propulsion Control & Health Management Architecture

Sensors

Sensing technology is the foundation upon which a PCHM system is based since it provides the raw data that is subsequently processed and interpreted for making engine control and maintenance decisions. Today's aircraft propulsion systems are equipped with a suite of control sensors (temperatures, pressures, rotor speeds, etc.) that are used as inputs by the engine control logic. Additionally, engines are typically equipped with a variety of instrumentation for health monitoring purposes and cockpit displays. This can include lubrication and fuel system sensors (e.g. pressure, temperature, and quantity), accelerometers, and gas-path instrumentation for performance monitoring purposes. Current research efforts are making critical advances in sensing technology. These include enhancements in the areas of weight, cost, accuracy, reliability, and robustness. It also includes the development of new sensors enabling measurement of previously unmeasurable parameters, which are critical for assessing the overall health of the propulsion system. This will enable a transition from manual inspection practices to automated condition assessments performed by an intelligent air vehicle. The candidate sensing technologies for flight test on the C-17 T-1 aircraft as identified by the PCHM Working group are summarized below:

Electrostatic Debris Monitoring Sensors. Gas path debris monitoring sensors for monitoring and quantifying engine debris ingestion and discharge are desirable for assessing the health of engine gas-path components [1,2,3]. These sensors employ an electrostatic technique to monitor and quantify the amount of electrostatically charged debris present in the engine. When mounted at the engine inlet these sensors would be able to detect the ingestion of foreign objects or debris. Additionally, debris monitoring sensors mounted near the engine exhaust hold the potential to detect debris generated by wear of turbine blades, abradable rub strips, seals, etc., the liberation of turbine blades/vanes, and variations in combustion by-products. An Inlet Debris Monitoring Sensor (IDMS) and an Engine Distress Monitoring Sensor (EDMS) are currently undergoing flight test on the C-17 T-1 aircraft. Additional information on these sensors can be found in Appendix B.1.1.

Stress Wave Analysis Sensors. Stress Wave Analysis (SWAN) sensors monitor structurally borne ultrasonic sound vibrations to measure energy created by shock or friction events [4]. These are externally mounted sensors which require a mount point that provides a mechanical sound path to the component being monitored. These sensors are promising for detecting incipient fault conditions in engine mechanical components. Currently several of these sensors are installed and undergoing flight testing on the C-17 T-1 aircraft. (See Appendix B.1.2.)

Oil Condition Monitor. An Oil Condition Monitor (OCM) sensor measures parameters related to the condition of the oil as well as the health of the oil system. Hot spots within the oil system can burn or scorch the oil and thereby change the oil electrical properties. Early detection of such conditions can prevent oil starvation of the engine bearing and consequently prevent catastrophic engine failure. The OCM is an in-line sensor that is designed to monitor lubricant coking in operational engines. The technique is based on the electrical conductivity of the fluid. Ester based lubricant generates charged particles that are conductive. These particles will tend to agglomerate as their concentration increases to the point where coke forms as varnish and under severe coking problems sludge and carbon deposits will form plugging oil nozzles and filters. (See Appendix B.1.3.)

Oil Debris Monitor. An oil debris monitor (ODM) sensor monitors for the presence of oil debris in the lubrication system generated by failure of critical lubricated components [5,6,7]. The sensor under consideration for flight test on the C-17 T-1 aircraft can determine particle size, particle count, and can distinguish between ferromagnetic and non-ferromagnetic particles. As such it is valuable for the early detection of incipient fault conditions such as bearing spalling events. (See Appendix B.1.4.)

Dynamic Pressure Sensor. High Temperature, high bandwidth pressure sensors are an enabling technology for active combustion control, active compressor control, burner screech detection, and propulsion health management applications. State-of-the-art dynamic pressure sensor technology is limited to benign applications, typically below 450° F. A sensor with a 1,400 F (max) ambient capability, 2,000 hour life, and 10,000 Hz bandwidth is envisioned. (See Appendix B.1.5.)

Silicon Carbide Sensing Capabilities. There are sections of a gas turbine engine that conventional sensing technology can not survive in due to the harsh thermal environment. Recent advances have been made in Silicon Carbide (SiC) sensing technology enabling sensors to survive in higher temperature environments. Some of the candidate SiC sensors for flight test on the C-17 T-1 include pressure, accelerometer, flow, and temperature sensors [8,9,10]. The additional measurements provided by these SiC sensors can further enhance the accuracy and visibility of aircraft engine diagnostics and controls technologies. (See Appendices B.1.6, B.1.7, and B.1.8.)

Optimal Ester and Hybrid Ceramic Bearings. Although not sensors, two additional technologies identified for potential flight test noted here are Optimal Ester and Hybrid Ceramic Bearings. A new “Optimal Ester” engine oil is being developed with superior thermal and tribological performance as well as lower coking tendencies. This could enable higher temperature operation and provide added resistance to oil degradation and coking. Testing of the new “Optimal Ester” in conjunction with an Oil Condition Monitor would provide valuable information. A Hybrid Ceramic Bearing has ceramic rolling elements and metal races. Hybrid Ceramic Bearing utilization in military systems could significantly enhance the extreme performance capabilities required. The increased capabilities of this type of bearing could also provide reliability and performance improvements for commercial systems. (See Appendices B.1.9 and B.1.10.)

Diagnostics & Prognostics

Diagnostics and prognostics are the algorithms (software) that make up a health management system. Diagnostics is the assessment of the current condition of the system, and the detection and isolation of any faults. Prognostics, predicts remaining component life based upon the past, and projected future, operating history of the system. Reliable diagnostics and prognostics collectively enable the optimal scheduling and performance of engine maintenance (which increases vehicle availability, reduces maintenance turn around time, and reduces unnecessary maintenance actions). Examples of diagnostic sub-systems include gas path analysis (assesses component performance/faults, assesses operability margins, and sensor & actuator fault detection and isolation), vibration diagnostics (mechanical component fault detection and isolation, rotor balance checks, etc.), and lubrication system diagnostics (checks for debris in oil, quality of oil). Prognostic sub-systems include trending component effective cycle counts for life usage monitoring purposes, and trending remaining engine margins such as Exhaust Gas Temperature (EGT). New information from advanced sensors, advanced algorithms and signal processing techniques, and enhanced life usage monitoring techniques are providing additional diagnostic/prognostic opportunities and challenges. The candidate diagnostic and prognostic technologies for flight test on the C-17 T-1 as identified by the PCHM Working group are summarized below:

HealthWatch. HealthWatch, developed by the NASA Ames Research Center, is a comprehensive diagnostic research tool used to collect vibration and oil debris data, and host diagnostic algorithms, for monitoring the health of critical engine mechanical

components. Flight data is critical to understanding the effect actual flight conditions have on diagnostic technologies developed in the laboratory environment, and assessing and reducing false alarms. For example, signal non-stationarity, a major cause of high false alarm rates, can only be determined on-line during flight. HealthWatch is a versatile tool that will allow analysis and diagnostic methodologies to be evaluated on-line in real-time during flight. (See Appendix B.2.1.)

Data/Information Fusion Technology. Data/Information fusion is the integration of data from multiple sources and related information to achieve more specific inferences than could be obtained by using a single sensor alone. Under a NASA contracted effort, Pratt & Whitney, Intelligent Automation Corporation, and Luppold & Associates are applying data/information fusion techniques to enhance aircraft gas turbine engine diagnostics and prognostics [11]. The demonstration application for this effort is the Pratt & Whitney F117 engine, which is the power plant for C-17 aircraft. The basic tenet of the data/information fusion concept is to leverage all available information to enhance diagnostic visibility, increase diagnostic reliability and reduce the number of diagnostic false alarms. (See Appendix B.2.2.)

Remote Diagnostics Server / Testability Engineering And Maintenance System – Real-Time (TEAMS RT). The Remote Diagnostic Server TEAMS RT tool provides technologies for automated diagnostics that can be utilized in a comprehensive health management architecture [12]. The Remote Diagnostic Server application that includes the TEAMS-RT embedded diagnostic reasoner can perform decision fusion based on inputs such as system sensed measurements and the results of other diagnostic algorithms. Flight testing the diagnostic reasoner embedded in flight hardware will validate its performance in the flight environment. Integration into the flight environment will provide end-to-end validation of the technology and characterization of interfaces to data systems and maintenance personnel. (See Appendix B.2.3.)

Hybrid On-board Model – Enhanced Self-Tuning On-board Real-time Model (eSTORM). An on-board self-tuning engine model provides the means to continuously monitor the performance of an aircraft engine over its lifetime of use, and can also be used for real-time engine fault diagnostics and control purposes. A hybrid on-board modeling approach, known as “eSTORM”, fuses a physics-based model with an empirical model forming a unique hybrid model for enhanced gas turbine engine diagnostic and prognostic purposes [13]. This work is being performed under a NASA SBIR with Intelligent Automation Corporation, with sub-contracting support from Luppold & Associates, and consultation support from Pratt & Whitney. Flight testing of the hybrid model will enable “real-world” validation of the technology. (See Appendix B.2.4.)

Probabilistic Life Models. Reliable aircraft engine component life usage models, which estimate life consumption based upon past operating history, are necessary to enable the transition from time-based to condition-based maintenance. These models will be

developed for select engine components, and will use available engine sensor measurements and model-predicted parameters to calculate component life consumption. They will provide a probabilistic life estimate to account for inherent system uncertainties such as material properties and measurement uncertainties. The benefits of reliable component life usage monitoring techniques include reduced engine maintenance costs and increase reliability. The envisioned prognostic and health management capabilities of future aircraft will require the maturation of this technology. (See Appendix B.2.5.)

Propulsion Malfunction Indication for Pilots. The FAA and Boeing Phantom Works are currently performing propulsion indication research on new cockpit indications, cautions, and warnings. The objective is to develop improved cockpit indications which will enhance the flight crew's ability to recognize and diagnose propulsion system malfunctions. Demonstration of these new concept features on a multi-engine airplane is highly desirable. This program is also developing a low cost engine monitoring system that can trend engine performance and provide cockpit alerts. Application of prototype technologies into a flying test-bed, such as the C-17 T-1, will allow developers to evaluate pilot-cockpit interfaces, procedures associated with information provided by the system, and requirements for overall operation. (See Appendix B.2.6.)

Disk Crack Detection. Cracks in aircraft engine rotor disks have been identified to cause a distinct behavior in the vibration response of rotor assemblies. Radial-axial cracks induce a unique vibration response as they open due to tensile hoop stresses caused by centrifugal loading. The crack opening forces a redistribution of the disk mass. This redistribution results in an additional unbalance that is proportional to the square of the speed, and hence the resulting crack-induced unbalance force is proportional to the fourth power of the speed. This unique unbalance force characteristic contrasts to the force due to standard mass unbalance, which is related to the square value of the speed. This knowledge has been utilized to develop an on-line monitoring system to detect early stage disk cracks in aircraft engines [14]. The approach consists in identifying the unique speed-dependence characteristic in the vibration signature of cracked disks by measuring the vibration response at non-invasive locations (e.g., bearings). This approach has been used in spin pit and engine tests. Flight tests are required to demonstrate vibration based disk fault detection system can be used in normal 'noisy' flight environment. (See Appendix B.2.7.)

Controls

Engine control logic is responsible for maintaining the safe, reliable and efficient operation of the engine over its entire operating envelope. Newer engines use digital control logic, which is typically housed in a Full-Authority Digital Engine Controller (FADEC) unit. Control inputs consist of a suite of gas path sensors such as temperatures, pressures, and rotor speeds. This information is used by the control to generate actuator commands such as fuel flow, bleed valve position, and variable vane position. The control logic is robustly designed to maintain engine performance (fuel burn, thrust) and

to maintain adequate margins (temperature, speed, etc.) to avoid compromising operability, safety, or life of the engine and its components. Current research efforts are underway to enhance engine control logic and to incorporate active control into the operation of engine components. The candidate controls technologies for flight test on the C-17 T-1 as identified by the PCHM Working group are summarized below:

Life Extending Control. Enhanced aircraft engine life extending control logic which can increase effective component life while maintaining the required performance is highly desirable as it can result in significant savings in aircraft engine operating costs [15,16]. Approaches include smart acceleration logic to minimize thermal peaks during transients, and adaptive control to optimize engine operation based upon the current condition of the engine. Both NASA and the US Navy have ongoing life extending control efforts which are candidates for flight testing on the C-17 T-1 aircraft. (See Appendix B.3.1 and B.3.2.)

Active Clearance Control. Aircraft engine turbine blade tip-to-case clearances will increase over an engines lifetime of use due to rubs and erosion. Active clearance control aims to address this issue by actively manipulating both transient and steady state turbine tip clearances during engine operation. The approach is to develop a control system which uses direct sensor feedback and smart structures to provide fast-response clearance control over the entire operating profile of the engine [17]. This will allow increased life due to decreased rubs and lowered EGT, as well as increased turbine efficiency. Flight testing of this technology does pose challenges as it will require a redesigned turbine casing, clearance sensors, hardware to control the turbine casing and software for active clearance control. However, flight testing is essential maturation step to quantify the technology benefits and reduce technology risk. (See Appendix B.3.3.)

Integrated Controls and Health Management

Research is moving in a direction towards a continued increase in the sophistication of aircraft engine controls and health management systems, and ultimately to an integration of these two technology areas. An engine that can in real-time automatically diagnose and adapt to its current condition promises to enhance the overall performance, reliability, safety, and availability of the vehicle. Such automated logic is currently implemented on a limited scale in today's engines. Sensor fault detection, isolation, and accommodation logic is currently used within the controller to automatically recognize and disqualify any faulty control sensor and revert to a physically redundant backup sensor. Enabled by the increased processing capability of today's microcomputers, recent research efforts in model-based controls and diagnostics have been conducted. This technology consists of a real-time on-board engine model embedded within the engine control logic. An on-line parameter estimation algorithm, or tracking filter, tunes the model to estimate off-nominal engine component performance, sensor bias, or actuator bias. This provides several benefits such as continuous real-time trending of engine health, synthesized sensor values (which can be used in sensor validation logic), and estimates of un-measurable engine parameters such as thrust and component stability

margins (which can then be used in feedback control logic). Research efforts are also being directed at developing propulsion control systems that can adapt based upon the condition of the specific engine, and also based upon changing requirements/objectives as commanded by a system-level vehicle management system. The candidate technologies for flight test on the C-17 T-1 as identified by the PCHM Working group are summarized below:

Adaptive Control for Performance Optimization. Conventional aircraft engine control logic is robustly designed to account for engine-to-engine manufacturing variations, and degradation effects which are inherent to the application. However, a performance penalty is paid in exchange for this added robustness. Research efforts are underway to develop advanced model-based adaptive control techniques to optimize engine performance in the presence of variations due to manufacturing tolerances and engine degradation due to "normal" usage. As the engine changes, the control will adapt to optimize performance in terms of fuel burn, thrust, and/or component life. (See Appendix B.4.1.)

Model-Based Fault Tolerant Control. In addition to performance optimization, model-based techniques can also provide fault detection and accommodation benefits [18]. An on-board model accurately tuned to match the performance of the physical engine enables real-time continuous monitoring of component performance and operability, and also provides synthesized parameter estimates for sensor/actuator fault diagnostic purposes. In the event a fault is detected, its effects can be mitigated via control accommodation. Using a model-based approach to tailor the fault detection and control accommodation logic to a specific engine allows smaller magnitude incipient faults to be diagnosed, and can reduce false alarms and missed detections. (See Appendix B.4.2.)

Autonomous Propulsion System Technology. This effort seeks to reduce or eliminate human dependency in the control and operation of aircraft propulsion systems. This technology includes a self-diagnostic adaptive engine control system that 1) Performs autonomous propulsion system monitoring, diagnosing, and adapting functions; 2) Combines information from multiple disparate sources using state-of-the-art data fusion technology; and 3) Communicates with a vehicle management system and flight control to optimize overall system performance. Such technology supports unmanned air vehicle (UAV) operation and would also enhance the safety of manned vehicles by reducing pilot workload. The challenge will be to ensure proper communication between bill of material engine control, the vehicle flight control, and the autonomous propulsion control logic to ensure safe operation. (See Appendix B.4.3.)

Propulsion Control for Integration with Intelligent Flight Control. NASA is currently conducting research in the area of intelligent flight controls which will have the capability to automatically adapt and reconfigure control responses to compensate for damage or changes to the aircraft. The objective of this activity is to enhance aviation safety by minimizing the impact damage has on the pilot's ability to maneuver the airplane. Past studies have shown that an aircraft's engines can be used as an alternate flight control effector in the event that the aircraft's normal flight control effectors are damaged or inoperable. Additional benefits could be gained through the development of

advanced propulsion system control modes, such as a rapid thrust mode or a maximum thrust mode, to provide additional control effectiveness in the use of engines as a primary flight control effector in the event of certain damage scenarios. (See Appendix B.4.4.)

NOTIONAL ROADMAP FOR FLIGHT TEST

Figure 2 shows a Notional Roadmap of the previously described candidate technologies for flight test on the C-17 T-1 organized into the four categories of sensors, diagnostics and prognostics, controls, and integrated controls and diagnostics. In general sensor technologies and passive health monitoring technologies appear earlier on the roadmap timeline as they require fewer aircraft modifications to install and fly. Controls and integrated controls and diagnostics technologies tend to require more extensive aircraft modifications, they need to be tailored to the particular engine, and must be properly interfaced with existing engine control hardware and software. As such they appear as slightly longer-term technologies in the notional roadmap. All technologies must receive the necessary safety approvals prior to undergoing installation and flight testing to ensure that the safety and operability of the vehicle is not compromised.

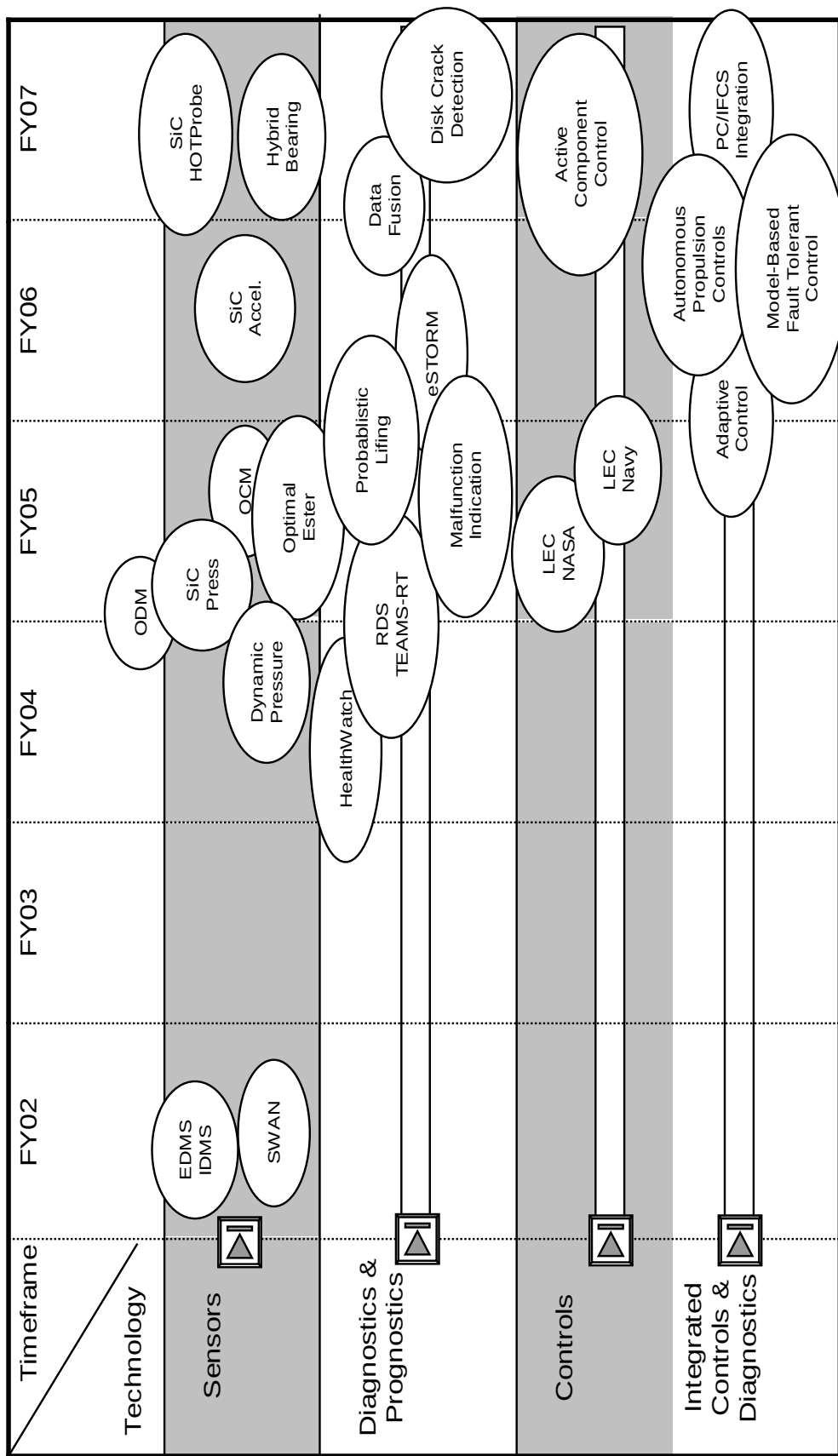


Figure 2. C-17 T-1 Propulsion Control and Health Management Technologies Notional Roadmap

PCHM BENEFITS AND RELATIONSHIP TO NASA GOALS

PCHM is a technology investment area that can directly support the NASA/FAA/DoD goal to enable a safer, more secure, efficient and environmentally friendly air transportation system [19]. This includes the objectives to 1) Decrease the aircraft fatal accident rate and the vulnerability of the air transportation system to threats and mitigate the consequences of accidents and hostile acts; 2) Protect local and global environmental quality by reducing aircraft noise and emissions; and 3) Enable more people and goods to travel faster and farther, with fewer delays.

Increased Safety

PCHM is intrinsic to enhancing aviation propulsion system safety. Early detection of incipient faults allows corrective maintenance to be performed before the fault escalates into a more serious event. In-flight diagnosis and accommodation of more abrupt faults can help reduce the severity of the malfunction and can also help the flight crew in recognizing and responding appropriately to the event in a timely manner. One of the major propulsion-related commercial aviation accident/incident categories is “Propulsion System Malfunction Plus Inappropriate Crew Response.” These are events where the pilot(s) did not appropriately handle a single benign engine or propulsion system malfunction. Inappropriate response includes incorrect response, lack of response, or unexpected or unanticipated response [20]. PCHM can play a significant role in addressing this accident category by providing the pilot with improved engine health information.

Increased Air Transportation System Mobility

Reliable PCHM can also enable the optimal scheduling and performance of engine maintenance. Performing maintenance that is based upon the condition of the engine, as opposed to following a strictly time-based maintenance schedule, can prevent the engine from being prematurely removed from service. Reliable diagnostics and prognostics can also yield reductions in unnecessary maintenance actions due to false alarms, and time expended by maintenance personnel in troubleshooting faults. Optimal control of the engine can also reduce the rate of component degradation and allow extended engine time-on-wing. Collectively these benefits can result in greater aircraft availability and reduced maintenance-related flight delays and cancellations thus increasing overall aviation capacity.

Reduced Emissions

Although conventional aircraft engine control logic is designed for a “nominal” engine, in reality a nominal engine does not exist. For example, performance will vary from engine-to-engine due to manufacturing variations. Additionally, performance will

degrade as the engine deteriorates over its lifetime of use. Nominal performance can be partially restored by advanced control schemes that recognize and adapt to the current condition of the engine. This can result in reduced fuel burn and reduced emissions. Additional reductions in fuel burn and emissions can be obtained through active component control, thereby enabling the engine to operate more efficiently.

Additional Benefits

PCHM can also greatly reduce engine operating costs. Optimal scheduling and performance of maintenance will result in extended engine time-on-wing, less unscheduled maintenance actions, less unnecessary maintenance actions, and less time spent troubleshooting faults all of which equates to reduced vehicle operating costs. Optimal control of the engine will result in reduced fuel burn and extended component life, which generate further reductions in operating costs.

Although the application focus of the Working Group was the C-17 aircraft, the PCHM technology is transferable to air-breathing access to space systems as well. For example, NASA's Integrated System Test of an Air-breathing Rocket (ISTAR) project plans to develop and test a Rocket-Based Combined Cycle (RBCC) engine system. As such, the PCHM technology discussed in this paper can potentially support additional NASA goals such as improving the safety, affordability, and reliability of future space transportation systems.

C-17 T-1 CAPABILITIES

The C-17 Globemaster III test plane, known as T-1, (Figure 3) is an Air Force flight research vehicle located at Edwards Air Force Base. NASA Dryden and the C-17 System Program Office (SPO) have entered into a Memorandum of Agreement to permit NASA DFRC the use of the C-17 T-1 to conduct flight research on a mutually coordinated schedule. The C-17 Globemaster III is a military transport aircraft capable of most operating environments used by both military and commercial transport aircraft. The Air Force fact sheet [21] on this vehicle provides the following description of the airplane: "The C-17 Globemaster III is the newest, most flexible cargo aircraft to enter the airlift force. The C-17 is capable of rapid strategic delivery of troops and all types of cargo to main operating bases or directly to forward bases in the deployment area. The aircraft is also capable of performing tactical airlift and airdrop missions when required. The inherent flexibility and performance of the C-17 force improve the ability of the total airlift system to fulfill the worldwide air mobility requirements of the United States." The aircraft provides extensive size and space for hosting experiments. The vehicle is equipped with four high bypass ratio Pratt & Whitney F117-PW-100 turbofan engines, each capable of delivering 40,440 pounds of thrust. These engines are derivatives of the PW2000 commercial engines used to power the Boeing 757 aircraft. Each engine is equipped with an Electronic Engine Control and a standard Bill-of-Material instrumentation suite. On the C-17 T-1, engine #3 is used as a research article and is

equipped with additional research flight test instrumentation including several advanced sensors undergoing flight test as part of a current NASA Dryden-led Propulsion Health Management (PHM) flight test program. The vehicle data acquisition system is capable of recording and archiving parameters from the aircraft and all four engines in addition to the propulsion research instrumentation. Furthermore, additional research signals can be added to the existing data acquisition system. The capabilities of the C-17 T-1 make it an ideal vehicle to host PCHM flight test experiments.

Upgrades to the C-17 T-1 aircraft will be necessary in order to host many of the candidate PCHM technologies under consideration for flight test. Dedicated processors to host the research propulsion controls and health management algorithms will have to be installed and properly interfaced to the aircraft through existing aircraft communication buses. These added processors will require the necessary data acquisition and data archival capabilities to accommodate the needs of any propulsion controls and health management technologies flown. In particular, steps need to be taken to ensure that any research propulsion control performs properly with the baseline control implemented in the Engine Control Computer (EEC). For example the baseline controller will require modifications to accept external digital inputs from a research propulsion controller, but it is envisioned that the baseline control will maintain all safety limit protection functionality. The appropriate safety analysis must be performed to ensure that any new software or hardware installed does not compromise the safety of the vehicle. Any proprietary issues associated with the baseline control will also have to be addressed in order to provide an open architecture for evaluating research control and health management algorithms.



Figure 3. Air Force C-17 T-1 Aircraft

CONCLUSIONS

Propulsion Control and Health Management is a technology investment area that has promise for enhancing aircraft safety, reducing aircraft operating costs, and increasing vehicle availability. The Air Force C-17 T-1 aircraft located at Edwards Air Force Base is uniquely suited to serve as a flight test-bed platform for the maturation of these technologies. Through the efforts of the C-17 PCHM Working Group, coordination between various government agencies conducting PCHM research has taken place and the capabilities of the C-17 T-1 aircraft to potentially host flight tests of PCHM technologies has been communicated. Candidate technologies for flight test on the C-17 T-1 have been identified and documented. This information will be beneficial to NASA for future planning purposes and in identifying any vehicle upgrades necessary to support the flight testing of the PCHM technology under consideration. Future steps will be required to obtain the necessary programmatic support and resources to take select PCHM technologies to actual flight test.

APPENDIX A: NASA TECHNOLOGY READINESS LEVELS DEFINITION

Technology Readiness Levels (TRLs) are a systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology [22]. The TRL approach is used within NASA for technology development planning and tracking. Definitions of the nine NASA TRLs are provided below.

- TRL 1:** Basic principles observed and reported
- TRL 2:** Technology concept and/or application formulated
- TRL 3:** Analytical and experimental critical function and/or characteristic proof-of-concept
- TRL 4:** Component and/or breadboard validation in laboratory environment
- TRL 5:** Component and/or breadboard validation in relevant environment
- TRL 6:** System/subsystem model or prototype demonstration in a relevant environment (ground or space)
- TRL 7:** System prototype demonstration in a space environment
- TRL 8:** Actual system completed and “flight qualified” through test and demonstration (ground or space)
- TRL 9:** Actual system “flight proven” through successful mission operations

APPENDIX B – CANDIDATE PCHM TECHNOLOGY FOR C-17 T-1 FLIGHT TEST

The following is a summary of the candidate PCHM technologies for flight test on the C-17 T-1 aircraft as identified by the C-17 PCHM Working Group. A C-17 PCHM Working Group Point of Contact (POC) is listed for each technology area. These individuals either wrote or collected the associated technical summary.

Appendix B.1 – Sensor Technology

Name	Description
B.1.1 Inlet Debris Monitoring System (IDMS) and Engine Distress Monitoring System (EDMS) [1,2,3]	C-17 PCHM Working Group POC: Mike Venti Technology Description: The IDMS consists of 2 conductive metallic strips located in the fan inlet. It monitors the electrostatic charge associated with debris ingested at the engine inlet. It is designed to detect the size, quantity, velocity and to a limited extent the composition of the debris. The EDMS is installed in the upper actuator housing of the core thrust reverser. It monitors the electrostatic charge of debris exiting the engine. The intent is to monitor the exhaust for changes in the level and nature of this debris. It is designed to detect problems related to blade damage, poor combustion, erosion, and FOD ingestion. Justification for Flight Test: Demonstrate the IDMS/EDMS and signal conditioning units function as designed on the C-17. Establish normal IDMS/EDMS baseline detection levels in different flight regimes. Determine IDMS ability to detect non-hazardous debris ingestions including normal sand and other debris ingested during take-offs, landings on different surfaces, and flying through cloud and wake turbulence. Evaluate the ability of the EDMS to evaluate any engine debris emission events with possible blade rubs, erosion, or ingested debris. Correlate IDMS and EDMS results with each other and with SWAN sensors and high frequency vibration accelerometers. Current Schedule & TRL: These sensors were installed on the airplane in Oct 2001. The IDMS sensors were removed in July 2002 after one of the strips came un-bonded. This incident is under investigation. TRL level in the 3 to 4 range. Schedule to Support Flight Testing: Installed in 2001. Flight Test-bed Requirements: Installed in 2001. Success Criteria for Flight Testing: Sensors survive flight test environment. No false alarms generated. Any debris properly detected.
B.1.2 Stress Wave Analysis (SWAN) [4]	C-17 PCHM Working Group POC: Mike Venti Technology Description: The Stress Wave Analysis (SWAN) is an integrated circuit piezoelectric transducer that monitors structurally borne ultrasonic sound vibrations to measure energy created by shock or friction events. It is an external sensor that requires a mount point that provides a mechanical sound path to the component being monitored. Five of these sensors are currently mounted on the engine gearbox and flanges of the C-17 T-1 aircraft. Justification for Flight Test: Demonstrate that the SWAN sensors function properly at a variety of mounts on the engine case and gearbox in the C-17 flight environment. Establish normal SWAN sensor baseline signatures at a variety of different mount points, engine operating states, and flight regimes. Correlate the signatures of different SWAN sensors as appropriate. Analyze the SWAN sensor data for evidence of shock and friction events both in cruise flight and under load, including hard landings and a variety of g loaded maneuvers. Correlate with EDMS and high frequency vibration accelerometers. Current Schedule & TRL: These sensors were installed on the airplane in Oct 2001 and are still on the airplane. TRL in the 3 to 4 range. Schedule to Support Flight Testing: Installed in 2001. Flight Test-bed Requirements: Installed in 2001. Success Criteria for Flight Testing: Sensor and on-line recording device survive flight test environment. No false alarms generated.

B.1.3 Oil Condition Monitor (OCM)	C-17 PCHM Working Group POC: Jon Dell & Ken Semega Technology Description: OCM is an in-line sensor that is designed to monitor lubricant coking in operational engines. The technique is based on the electrical conductivity of the fluid. Ester based lubricant generates charged particles that are conductive. These particles will tend to agglomerate as their concentration increases to the point where coke forms as varnish and under severe coking problems sludge and carbon deposits will form plugging oil nozzles and filters. The OCM as currently configured consists of an on-line sensor connected into an oil line by a "T" at some convenient location. The sensor has a small data recording device attached. No other on-line data recording is required. After completion of a flight a card is removed from the device and the data is read by ground support equipment (a card reader). Justification for Flight Test: Payoffs: The OCM sensor obtains information on the condition of the oil as well as the health of the oil system. Normally hot spots within the oil system will burn or scorch the oil and thereby change the oil electrical properties. Early detection of such condition will prevent oil starvation of the engine bearing and consequently prevent catastrophic engine failure. Flight testing will contribute to accelerated field incorporation. Current Schedule & TRL: The sensor has been developed and the unit will be made available as required for this testing. Schedule to Support Flight Testing: The sensor is available. A card reader will need to be procured which will take about 30 days. Flight Test-bed Requirements: A plumbing connection in the oil line is required that consists of a T-connection. The location of this connection in the oil system is not critical. Success Criteria for Flight Testing: Sensor and on-line recording device survives flight test environment. No false alarms generated. Oil degradation properly indicated if it occurs.
B.1.4 Oil Debris Monitor (ODM) [5,6,7]	C-17 PCHM Working Group POC: Paula Dempsey Technology Description: Oil debris data will be collected using a commercially available oil debris sensor. The sensor monitors for the presence of oil debris in the lubrication line generated by failure of critical lubricated components. The sensor consists of three coils surrounding a nonconductive section of tubing. Two coils are wound in opposite directions and are driven by an alternating current source. Disturbance of the magnetic field, when a metal particle passes, produces an electrical signal that is measured by the sensor. The amplitude of the sensor output signal is proportional to the particle mass. The sensor can measure ferromagnetic and non-ferromagnetic particles based on the phase shift of the signal. Justification for Flight Test: Replacing single sensor limits with multi-sensor systems integrating different measurement technologies results in a system with improved damage detection and decision-making capabilities. Oil debris and vibration based measurement technologies used for turbine engine bearing diagnostics can be fused to maximize the beneficial information beyond that which can be obtained from each individual sensor. Flight data is required to establish normal baseline signatures of fused oil debris and vibration algorithms. The in-flight data will also be used to assess the false alarm rate of the associated diagnostic algorithms. Current Schedule & TRL: A sensor modification for installation in the aircraft was provided by Pratt & Whitney. The sensor will be procured from Gastops Ltd. Installation schedule is determined by Dryden. Schedule to Support Flight Testing: To be determined. Flight Test-bed Requirements: The sensor will interface with the aircraft Comprehensive Engine Diagnostic Unit (CEDU), or the HealthWatch system. The feasibility of interfacing with these two systems is currently under investigation. Success Criteria for Flight Testing: Demonstrate that the fusion of vibration and oil debris measurement flight data results in reduced false alarms.

B.1.5 Dynamic Pressure Sensor	C-17 PCHM Working Group POC: Ken Semega Technology Description: High Temperature, high bandwidth pressure sensors are an enabling technology for active combustion control, active compressor control, burner screech detection, and propulsion health management (PHM) applications. State-of-the-art (SOA) dynamic pressure sensor technology is limited to benign applications, typically below 450 F. SOA technology is life limited at these temperatures. Design trade-offs for higher temperature, robust applications result in reduced bandwidth. A sensor with a 1,400 F (max) ambient capability, 2,000 hour life, and 10,000 Hz bandwidth is desired. Potential advanced technologies in development include Silicon-on-Insulator (SOI) piezoresistive sensors, Silicon Carbide (SiC) sensors, LIGA MEMs devices, and sapphire or other high temperature optics. The development of active control sensors for this application also promises a pathway to high temperature, robust capability. Note: Not all of the applications require 1400 F operation. Expected applications will range from 600 F to 1400 F, all higher than current SOA capability. Justification for Flight Test: Because the use of dynamic pressure sensor technology is critical to certain applications, the transition path must include flight testing as soon as practical. Current Schedule & TRL: Dynamic pressure sensor technology is being developed under an Air Force Research Laboratory sponsored effort with the Ohio Aerospace Institute (OAI) and also a new FY03 SBIR topic. Depending on the application and specific technology, the TRL level is between 2 and 4. At the end of the OAI and SBIR Phase II efforts, the expected TRL level should be between 4 and 6, expected to occur in FY05. (The LIGA MEMs devices are the least mature, while the piezoresistive SOI are becoming mature). Schedule to Support Flight Testing: The OAI and SBIR programs are expected to take 36 months to complete. The TRL level of the technology is expected to be 5 at the conclusion of the two efforts. Additional, but currently unfunded rig testing after these efforts might be required to bring the TRL to level 6. Flight Test-bed Requirements: Specific flight test requirements have not been established because these are new programs. Success Criteria for Flight Testing: Success criteria are the accuracy and life of the sensor for the test. Temperature capability should be thoroughly proven during laboratory and rig tests.
B.1.6 Silicon Carbide (SiC) Pressure Sensor[8]	C-17 PCHM Working Group POC: Don Simon Technology Description: A single crystal hermetically sealed 6-H-SiC pressure transducer that operates at 600 C. This methodology offers the unique features that enabled successful sensor operation at 600 C. This is beyond the capability of conventional sensor technologies. These next generation sensors are geared toward weight reduction, improved accuracy of instrumentation and computational fluid dynamics coding. Benefits of the technology include: - Single crystal SiC offers excellent thermomechanical properties - Appreciably high gauge factor extendable to higher temperature operation (>500 C) - Compatible with SiC integrated circuit fabrication - Its near-inert surface chemistry means it is extremely resistant to corrosive environments - Survives in high radiation fields - These attributes make SiC piezoresistive sensors ideal for harsh environment applications Justification for Flight Test: Testing in a real operating environment will help validate performance metrics of the sensors, identify functional limitations, and reliability, and will support engine model validation. Current Schedule & TRL: FY02: Demonstrate sensor operation with improved packaging; Demonstrate model for signal conditioning algorithm. TRL 4. Schedule to Support Flight Testing: To be determined. Flight Test-bed Requirements: Access to multiple test points (for vibration, pressure, and temperature monitoring) in test-bed to compare, validate, and discriminate outcomes; On-board signal conditioning electronics for real-time sensing and control; Interfaces between sensor and on-board electronics and control algorithms; Simultaneously (or alternatively), will require ground or on-board data recording for post flight data review and reduction; Four wires per sensor (Wheatstone Bridge configuration requires two for power and two for output). Success Criteria for Flight Testing: To be determined.

B.1.7 Silicon Carbide (SiC) Accelerometer Sensor [9]	<u>C-17 PCHM Working Group POC:</u> Don Simon <u>Technology Description:</u> A single crystal 6H-SiC accelerometer that operates at 600 C. This methodology offers the unique features that enabled successful sensor operation at 600 C and from low- to high-g loads, beyond the capability of conventional sensor technologies. Benefits of the technology include: - Single crystal SiC offers excellent thermomechanical properties - Appreciably high gauge factor extendable to higher temperature operation (>500 C); - Compatible with SiC integrated circuit fabrication - Its near-inert surface chemistry means it is extremely resistant to corrosive environments - Survives high g environment - These attributes make SiC piezoresistive sensors ideal for harsh environment applications <u>Justification for Flight Test:</u> Insertion of these accelerometers in high temperature section of the engine (i.e., P4 and P5) for vibration analysis. It may potentially overcome the limitations of current accelerometers in use. The high natural frequency provides high bandwidth measurement capability. <u>Current Schedule & TRL:</u> TRL between 3 and 4. <u>Schedule to Support Flight Testing:</u> Technology is mature for insertion in test flights. Will need pre-calibration. On- or off-chip signal conditioning protocol is yet to be implemented. <u>Flight Test-bed Requirements:</u> On-board data recording; Four terminal circuit interface required. <u>Success Criteria for Flight Testing:</u> To be determined.
B.1.8 Silicon Carbide (SiC) High Operating Temperature Probe (HOTProbe) [10]	<u>C-17 PCHM Working Group POC:</u> Don Simon <u>Technology Description:</u> SiC High Operating Temperature Probe (HOTProbe) SiC chip to simultaneously measure flow velocity, pressure, and temperature; Plug'n play capability; Operating temperature up to 600 C; High sensitivity. <u>Justification for Flight Test:</u> Testing in real operating environment will help validate performance metrics of the sensors, identify functional limitations and reliability, and support validation of realistic engine models. <u>Current Schedule & TRL:</u> FY02: Demonstrate sensor operation with improved packaging; Demonstrate model for signal conditioning algorithm. TRL 2. <u>Schedule to Support Flight Testing:</u> To be determined. <u>Flight Test-bed Requirements:</u> Access to multiple test points (for vibration, pressure, and temperature monitoring) in test-bed to compare, validate, and discriminate outcomes; On-board signal conditioning electronics for real-time sensing and control; Interfaces between sensor and on-board electronics and control algorithms; Simultaneously (or alternatively), will require ground or on-board data recording for post flight data review and reduction; Four wires per sensor (Wheatstone Bridge configuration requires two for power and two for output). <u>Success Criteria for Flight Testing:</u> To be determined.

B.1.9 Optimal Ester	C-17 PCHM Working Group POC: Jon Dell Technology Description: A new “Optimal Ester” engine oil is being developed with superior thermal and tribological performance as well as lower coking tendencies. In order to achieve an operational temperature range of -40° to 450°F with this class of oil, both the base fluid and additive package will need to be optimized. The optimal ester will also have improved film thickness with a target kinematic viscosity range of 5.5 to 7.0 centiStokes @ 100°C (MIL-PRF-7808, Grade 4 has a kinematic viscosity of 4.0 centiStokes @ 100°C). One of the diagnostic systems proposed for evaluation in the PCHM diagnostic flight test is an Oil Condition Monitor (OCM). The purpose of that device is to monitor the condition of the oil to detect chemical degradation, for example degradation due to exposure to high temperature conditions. The OCM will provide a warning when an internal engine malfunction exists allowing unacceptably high temperatures at some point in the lubrication system. The OCM will also provide a warning of oil degradation due to some types of contamination. Evaluation of the OCM in conjunction with the Optimal Ester oil as well as other currently in service oils such as MIL-PRF-7808 and MIL-PRF-23699 would be valuable. Justification for Flight Test: Availability of an improved oil with higher operating temperature capability would be of great benefit for both new design and legacy engine aircraft systems. It would enable higher performance capability for new systems and provide margin and growth capability for legacy systems. The F22 SPO is very interested in the optimal ester due to the greater margin for coking, as well as allowing the lubrication system to run hotter which would result in less heat transfer to the fuel as well as back to the airframe. This oil is in development and is expected to be compatible with currently used oils. Optimal ester oil could be incorporated into PCHM flight testing with minimal support requirements. Flight testing would provide a very beneficial means to evaluate both the performance characteristics of the optimal ester lubricant as well as the response and characteristics of the OCM and any other diagnostic devices potentially affected by the use of this oil. Current Schedule & TRL: Most Phase I and II in-house laboratory tests (TRL 3) were completed on the current optimal ester candidate in FY01/02. Bearing Deposition and Ryder gear testing (TRL 4) is scheduled for Sep 02. If target performance requirements are met, an in-house mini-lube simulator will be run (TRL 4) in ~Nov 02, followed by the full-scale T63 engine qualification test (TRL 5) in Jan 03. Schedule to Support Flight Testing: If the current sole candidate continues to perform well and meet all target requirements of the remaining tests, the oil could potentially be ready for flight testing in FY04. Estimated cost to reach mature technology for flight test readiness: \$350K. If additional formulation changes need to be made by the lubricant vendor at the TRL 4 or 5 level, this would add substantial time and costs to the plan and depends on how much R&D funding and effort the manufacturer is willing to put into this program. Currently, we have no other candidates in hand. Company mergers over the last several years in this technical community have lead to a limited number of vendors having the skilled personnel, financial backing, and patience to work on a research program with no guaranteed level of production. Flight Test-bed Requirements: The only flight test-bed requirements to support this testing would be that required to store, segregate and service the engine with this oil. Although an additional requirement in order to evaluate the benefits of the new oil would be access to oil wetted parts during post test engine teardown in order to evaluate their condition. Based on MIL-PRF-7808, Grade 4 flight testing, a minimum of 400 flight hours would be recommended to enable evaluation of the affect of the use of the new oil on oil wetted parts. Such affects might be reduced coking or varnish deposition and wear. Success Criteria for Flight Testing: There are no specific success criteria for flight test of this oil relative to diagnostics. The diagnostics success criteria for the test relative to this oil would be the accurate evaluation of the affects of this oil on the performance of diagnostic devices that may be affected by the type of oil used. Success criteria of the oil performance for flight testing the optimal ester fluid would be improved part condition as observed during a partial (e.g. #5 bearing area) or full engine teardown.
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B.1.10 Hybrid Ceramic Bearing	<u>C-17 PCHM Working Group POC:</u> Jon Dell <u>Technology Description:</u> A Hybrid Ceramic Bearing has ceramic rolling elements and metal races. A Hybrid Ceramic Bearing has been designed for the #3 bearing position in the F117 engine and ground tested both in rig testing and for 250 hours in an engine test (reference WL-TR-97-2057). Hybrid Ceramic Bearing utilization in military systems could significantly enhance the extreme performance capabilities required. The increased capabilities of this type of bearing could also provide reliability and performance improvements for commercial systems. Eleven new un-run bearings from the above referenced program are available and could be delivered to Dryden for flight test immediately. <u>Justification for Flight Test:</u> Incorporation of seeded fault Hybrid Ceramic Bearing spall testing into the C-17 PCHM test program would significantly enhance the diagnostic value of the test for all the diagnostic devices that may have the capability to detect the event by providing an excellent opportunity to evaluate their diagnostic capability. A Hybrid Ceramic Bearing spalling event behaves in a manner very similar to a conventional bearing spalling event. The working contact in a Hybrid Ceramic Bearing is an interface between ceramic and steel material and when spalling begins metal spalling debris is generated just as in a conventional all metal bearing spalling event. The vibration signature would also be expected to be nearly identical with that of a conventional bearing spall. Thus incorporation of this testing would validate diagnostic device capability to detect conventional bearing spalls. Some small differences which may or may not be discernable may exist in the vibration signature and some probably small amount of ceramic debris would be liberated in a Hybrid Ceramic Bearing spall event which would not be the case for conventional bearings. Evaluation of diagnostic detection capability of this ceramic debris would be of interest. Incorporation of seeded fault testing using this type of bearing in the C-17 PCHM test program would accelerate incorporation of Hybrid Ceramic Bearings into man-rated systems by providing better understanding of the diagnostic coverage available in the rare event of such a failure in service. It would also provide a real event signature for evaluating diagnostic systems. The value of flight test may greatest for vibration detection systems by providing them an opportunity to detect a real event in a real flight background vibration environment. <u>Current Schedule & TRL:</u> A bearing is now available for test. The technology readiness of the Hybrid Ceramic Bearing is about TRL 5. An enhancement of Hybrid Ceramic Bearing technology utilizing more advanced metal material races is in progress. A bearing utilizing this advanced configuration could also be made available in the latter part of the proposed FY03-FY07 time frame however funding would be required to design and manufacture the specific C-17 configuration bearing. The technology readiness at that time is expected to be about TRL 7. <u>Schedule to Support Flight Testing:</u> A bearing is available for testing. Flight safety review and approval is the only step required before testing. Bearing spalling events are rather gradual failure modes. The safety risk is not expected to be great especially in a highly instrumented multi-engine aircraft. Installation of the number three bearing into the engine requires access during an extensive engine teardown. A short time after the spalling event another extensive teardown would be required to remove the bearing. <u>Flight Test-bed Requirements:</u> Flight safety review and approval is required before testing. Installation of the number three bearing into the engine requires access during an extensive engine teardown. A short time after the spalling event another extensive teardown would be required to remove the bearing. These are the only flight test-bed requirements. <u>Success Criteria for Flight Testing:</u> There are no specific success criteria for flight test of the Hybrid Ceramic Bearing. The success criteria for the test relative to the Hybrid Ceramic Bearing would be the effectiveness of each diagnostic device in detecting the spalling event.
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Appendix B.2 – Diagnostics & Prognostics

Name	Description
B.2.1 HealthWatch	<u>C-17 PCHM Working Group POC:</u> Dr. Ed Huff & James Zakrajsek <u>Technology Description:</u> HealthWatch is a comprehensive diagnostics research tool used to collect vibration and oil debris monitoring data for critical mechanical components in the engine on-line during flight. HealthWatch is a versatile tool that will allow analysis and diagnostics methodologies to be evaluated real-time in-flight. <u>Justification for Flight Test:</u> Flight data is critical to understanding the effect actual flight conditions have on diagnostic technologies developed in the laboratory environment. Experimental data with simulated and seeded component faults is important in developing diagnostic methods that will react to damage. Flight data is critical in assessing and reducing the false alarm aspect of laboratory developed diagnostic techniques. Signal non-stationarity, a major cause of high false alarm rates, can only be determined on-line during flight. <u>Current Schedule & TRL:</u> FY03: Installation of HealthWatch in data collection mode only FY04+: Add capability for real-time signal analysis in HealthWatch <u>Schedule to Support Flight Testing:</u> Currently ready for flight operations. <u>Flight Test-bed Requirements:</u> Sensors: Accelerometers, On-Line Oil Debris Monitor, speed pulse. <u>Success Criteria for Flight Testing:</u> Comprehensive understanding of flight effects on diagnostic methods, including signal non-stationarity, and development of technology to overcome flight-effect, with minimum false alarm rates resulting.
B2.2 Data Fusion [11]	<u>C-17 PCHM Working Group POC:</u> Don Simon <u>Technology Description:</u> Data fusion is the integration of data from multiple sources and related information to achieve more specific inferences than could be obtained by using a single sensor alone. This task is a contracted effort with Pratt & Whitney, IAC, and Luppold & Associates. It is applying data fusion techniques to enhance aircraft gas turbine engine diagnostics and prognostics. The demonstration platform is the C-17 aircraft F117 engine. <i>Assets:</i> Software algorithms. <i>Technical Challenges:</i> Establishing a rich engine instrumentation suite, aligning data collected at multiple sample rates, obtaining rich dataset for technology development, establishing accurate fault & detection probabilities. <u>Justification for Flight Test:</u> Flight test environment provides “real-world” validation of data fusion technology. The expanded PHM advanced sensor suite on the C-17 T-1 aircraft makes it an ideal demonstration platform. <u>Current Schedule & TRL:</u> FY04 - TRL 3. Current planned work culminates with a ground-based demonstration using flight data inputs. <u>Schedule to Support Flight Testing:</u> 2 Years, \$2M. Risk: Obtaining adequate resources (people & \$), obtaining adequate on-board processing & on-board sensor suite. <u>Flight Test-bed Requirements:</u> Rich suite of engine instrumentation; Real-time on-board processing; Flight profiles & hours: TBD. <u>Success Criteria for Flight Testing:</u> System does not generate false alarms; System correctly detects and isolates any actual or simulated engine faults.

B.2.3 Remote Diagnostics Server/TEAMS RT [12]	C-17 PCHM Working Group POC: Ann Patterson-Hine Technology Description: Technologies for automated diagnostics that can be utilized in a comprehensive health management architecture will be flight tested on the C-17. The Remote Diagnostic Server application that includes the TEAMS-RT embedded diagnostic reasoner will perform decision fusion based on inputs such as aircraft measurements and the results of GRC data fusion algorithms. Justification for Flight Test: Health monitoring and diagnostics includes the development of several core capabilities that are necessary to achieve the program goal of autonomous flight control. Flight testing the diagnostic reasoner embedded in flight hardware will validate its performance in the flight environment. Integration into the flight environment will provide end-to-end validation of the technology and characterization of interfaces to data systems and maintenance personnel. Current Schedule & TRL: Currently at TRL 4. Phase 1: Pallet demonstration to go to TRL 5, 6 months after pallet computer ready; Phase 2: REFLCS integration to go to TRL 6, 6 months after completion of pallet experiment. Schedule to Support Flight Testing: Phase 1 will utilize the TEAMS-RT software currently available and the F-117 engine model currently under development by Pratt & Whitney and Qualtech. Software “hooks” between the engine model and available engine data from the flight system may need modest modification. Modifications to TEAMS-RT to support available OS may be needed, but are expected to be minimal (TEAMS-RT is currently available for Windows and VxWorks). Flight Test-bed Requirements: Phase 1: Addition of engine fault codes to master database. Addition of TEAMS-RT results to database. Pallet computer and interfaces, access to a/c data bus to get engine fault codes. External interface for communicating with pallet host computer for software upgrades and data downloads/presentation. Phase 2: Integration with data fusion algorithms to incorporate advanced sensor data. Integration into REFLCS. Success Criteria for Flight Testing: Demonstration of real-time performance of the health monitoring algorithms in the flight environment, including electronically seeding faults into the data stream with analysis performed by the pallet/flight computer.
B.2.4 Hybrid On-board Model (eSTORM) [13]	C-17 PCHM Working Group POC: Don Simon Technology Description: Fuses a physics-based model with an empirical model forming a unique hybrid model for enhanced gas turbine engine diagnostic and prognostic purposes. This gas-path performance model accurately matches measurable engine outputs as well as internal component health conditions. This work is being performed under a NASA SBIR with Intelligent Automation Corporation. The application is the C-17 aircraft F117 engine. Assets: Software algorithms. Technical Challenges: Establishing accurate model performance over entire operating envelope including transients. Justification for Flight Test: Flight test environment provides “real-world” validation of hybrid model technology. Expanded PHM advanced sensor suite on C-17 T-1 aircraft makes it an ideal demonstration platform. Provides an accurate on-board gas path model which is a cornerstone PHM technology. Current Schedule & TRL: FY04 - TRL 4 Current planned work culminates with a ground-based real-time demonstration using flight data inputs. Schedule to Support Flight Testing: 1.5 Years, \$1M Risk: Obtaining adequate resources (people & \$), obtaining adequate on-board sensor suite. Flight Test-bed Requirements: Rich suite of gas-path engine instrumentation; Real-time on-board processing; Flight profiles & hours: TBD. Success Criteria for Flight Testing: Hybrid model achieves improved estimation accuracy vs. conventional physics-based on-board self-tuning model.

B.2.5 Probabilistic Life Modeling	<u>C-17 PCHM Working Group POC:</u> Ken Semega <u>Technology Description:</u> The Probabilistic Life Model effort funds the development of algorithms to predict C-17 engine component life. Three engine components (such as turbine, compressor, etc) will be selected for life model development after a complete review of various C-17 databases (field data from over 300 engines). Pratt & Whitney will develop algorithms and code to implement Orthogonal Decomposition, regression, and neural network life models. A review of advanced (C-17) sensor data will be accomplished to provide potential improvements and capability for the life models. Use of the best technique (Orthogonal Decomposition, regression, or neural network technology) will provide a significant reduction in (monitoring system) data storage requirements as well as increased fault coverage of the component (not just a single point on a blade). "C" code will be written and downloaded into an engine diagnostic computer for ground test engine demonstration. Benefits expected are a significant reduction in engine maintenance cost. <u>Justification for Flight Test:</u> The use of on-board models is a pathway to reduced engine maintenance and life cycle cost. Planned PHM capability for advanced aircraft will require maturation of these technologies. <u>Current Schedule & TRL:</u> The probabilistic life models effort is a 36 month effort that will conclude with validation testing of code on engine CEDU hardware in the laboratory. Laboratory testing to validate the models will conclude at the end of 2004. Potential demonstrator tests and hardware in the loop testing is being considered for 2005. A TRL level of 4 is expected after laboratory demonstration, and TRL level of 5 after potential engine demonstrator testing. <u>Schedule to Support Flight Testing:</u> The major risk in developing code for flight test is demonstrating suitability for operation on CEDU engine hardware. Advanced Life algorithms require additional computational resources compared with current diagnostic approaches. <u>Flight Test-bed Requirements:</u> Specific hardware requirements and test time will not be specified until high level (such as C) code is written for the component models. <u>Success Criteria for Flight Testing:</u> The true success criteria for the Life Models will require many hours of flight testing. Of course, a zero false alarm rate is desired, but it alone is not a success criteria.
B.2.6 Propulsion Malfunction Indication for Pilots	<u>C-17 PCHM Working Group POC:</u> Bill Emmerling <u>Technology Description:</u> The FAA and Boeing Phantom Works are currently performing propulsion indication research which we expect will yield new cockpit indications, cautions, and possibly warnings. Demonstration of these new concept features for flight safety on a multi-engine airplane is highly desirable. Program is developing a low cost engine monitoring system that can trend engine performance and provide cockpit alerts. Application of prototype technologies into a flying test-bed allows developers to evaluate pilot-cockpit interface, procedures associated with information provided by the system, and requirements for overall operation. <u>Justification for Flight Test:</u> Flight testing is an obvious source for potential data that can be gathered from engine rigging changes to understand the variability of a normal operating engine. Nominal out of balance and other faults are of interest. This NASA flight test program will also develop/demonstrate as appropriate the high risk technology identified in the FAA Propulsion Indications Research effort. <u>Current Schedule & TRL:</u> Anticipate system to be available in FY04. <u>Schedule to Support Flight Testing:</u> To be determined. <u>Flight Test-bed Requirements:</u> To be determined. <u>Success Criteria for Flight Testing:</u> Demonstrate that the system provides accurate engine malfunction indication to the pilot with high reliability.

B.2.7 Disk Crack Detection [14]	<u>C-17 PCHM Working Group POC:</u> Jim Zakrajsek <u>Technology Description:</u> Cracks in rotor disks have been identified to cause a distinct behavior in the vibration response of rotor assemblies. Radial-axial cracks induce a unique vibration response as they open due to tensile hoop stresses caused by centrifugal loading. The crack opening forces a redistribution of the disk mass. This redistribution results in an additional unbalance that is proportional to the square of the speed, and hence the resulting crack-induced unbalance force is proportional to the fourth power of the speed. This unique unbalance force characteristic contrasts to the force due to standard mass unbalance, which is related to the square value of the speed. An on-line monitoring system to detect early stage disk cracks in aircraft engines would be available for flight tests. The approach consists in identifying the unique speed-dependence characteristic in the vibration signature of cracked disks by measuring the vibration response at non-invasive locations (e.g., bearings). <u>Justification for Flight Test:</u> This approach has been used in spin pit and engine tests. Flight tests are required to demonstrate vibration based disk fault detection system can be used in normal 'noisy' flight environment. <u>Current Schedule & TRL:</u> On-line disk crack detection monitoring system will be demonstrated in TF41 engine test at Navy China Lake facility at beginning FY03. Expected TRL level at end of tests is 5. <u>Schedule to Support Flight Testing:</u> 1 Year, \$500K. <u>Flight Test-bed Requirements:</u> Accelerometers need to be mounted on the engine housing. On-line data acquisition and monitoring system will be provided. System requires a speed sweep during start up. <u>Success Criteria for Flight Testing:</u> Demonstration that disk crack detection system will produce no fault alarms and will be insensitive to engine disassemble conditions and aircraft flight operating conditions.
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Appendix B.3 – Controls

Name	Description
B.3.1 Life Extending Control (NASA) [15,16]	<u>C-17 PCHM Working Group POC:</u> Sanjay Garg <u>Technology Description:</u> Modify engine control logic to increase effective component life while maintaining the required performance. One approach is that of using smart acceleration logic - "Design of An Intelligent Life Extending Control for Turbine Engines" by Link Jaw et al, 2001 American Control Conference. Software logic to be implemented will be available. There should be no technology risks since the control logic would have been validated via off-line simulation prior to flight test. <u>Justification for Flight Test:</u> Preliminary technology development has shown significant potential for reducing thermo-mechanical fatigue by adjusting the acceleration schedule during start up transients. It is important to conduct flight tests to ensure that the performance changes are acceptable to the pilot and also to get actual flight data to show that the LEC logic does result in temperature reduction at the critical components as indicated by the simulations. <u>Current Schedule & TRL:</u> Expected TRL is 4 by end of FY04. <u>Schedule to Support Flight Testing:</u> An additional \$300K and 5 month effort will be required to develop technology to flight readiness level. There are no perceived risks. <u>Flight Test-bed Requirements:</u> Some hardware modifications might be needed to place temperature sensors in the hot gas path components. Propulsion control modification will be required. The flight profile requirement is benign - general cycle of take-off, cruise and landing - about 20 cycles. <u>Success Criteria for Flight Testing:</u> Success criteria is that measurable reductions in temperature transients are obtained for typical "flight cycle" operation without any degradation in performance noticeable to the pilot.
B.3.2 Life Extending Control (Navy)	<u>C-17 PCHM Working Group POC:</u> Ken Semega <u>Technology Description:</u> These potential efforts will build on the Navy's, Life Extending Control work with Pratt & Whitney/ UTRC. Their work results in real-time trade-offs between engine specific fuel consumption and component life. End products of the Navy effort are control optimization algorithms that impact engine life. Air-Force efforts will focus on implementation aspects of Life Extending Control, which includes architecture, hardware, real-time software, and certification issues. Program goals are to develop the technology for the implementation of both life management models and life control modes on turbine engines. The development will focus on three key factors, real-time operation, engine integration, and compatibility with advanced sensors. Critical to the success of the effort is demonstration of the technology on an advanced Engine Diagnostic Unit (EDU) and Full Authority Digital Engine Control (FADEC). <u>Justification for Flight Test:</u> Life extending controls or control modes have many potential benefits for the Air Force, and Navy engine fleet. Additionally, commercial engines may benefit (in terms of operational cost-reduction) from certain control modes. <u>Current Schedule & TRL:</u> The Navy's work with Pratt & Whitney and UTRC is ongoing. This work is planned to be accomplished at the start of FY03 and another effort at the start of FY04. At the end of the Navy program, the TRL level will be 3 (proof of concept). Follow-On work should result in TRL levels of 4-5. <u>Schedule to Support Flight Testing:</u> The current work does not address flight testing. Potential Air Force efforts starting in FY03 and FY04 will plan for demonstration testing leading to future flight testing. <u>Flight Test-bed Requirements:</u> The full range of requirements for flight testing have not been evaluated to date. <u>Success Criteria for Flight Testing:</u> To be determined.

B.3.3 Active Clearance Control [17]	C-17 PCHM Working Group POC: Sanjay Garg Technology Description: There are many activities ongoing in active component control, however, the one that will benefit most from flight testing is "High Bandwidth Active Clearance Control". The idea is to use smart structures to intelligently control the clearance between the high pressure turbine blades and the turbine casing. This will allow increased life due to decreased rubs and lowered EGT, as well as increased turbine efficiency. Assets expected to be available are a redesigned turbine casing, clearance sensors, hardware to control the turbine casing and software for active clearance control. There are significant challenges to developing a whole new turbine casing. Justification for Flight Test: Flight test demonstration is essential to quantify technology benefits and reduce technology risk. Will leverage any flight test assets from test of clearance sensors. Current Schedule & TRL: Current plans are to take the technology to TRL3 by end of FY05. Schedule to Support Flight Testing: Significant additional funding investment, >\$2M, and time, >2 years, will be required to make the technology ready for flight test. Significant risk in designing a new casing for an existing engine. Flight Test-bed Requirements: Significant hardware changes will have to be made and flight certified for safety. Apart from the new casing, modifications will be required to put clearance sensors. Integration with the bill of material control will be needed to ensure safe operation. The flight profile requirement is a little more aggressive - apart from the take-off, cruise, landing cycle, additional maneuvers such as re-accel during cruise will be required. Total of 20 flight cycles will suffice to demonstrate the benefit. Success Criteria for Flight Testing: Demonstrate the capability to "tightly" control turbine clearance during typical aircraft operation transients.
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Appendix B.4 – Integrated Controls & Diagnostics

Name	Description
B.4.1 Adaptive Control for Performance Optimization	C-17 PCHM Working Group POC: Sanjay Garg Technology Description: Adapt engine control to match the "nominal" engine performance in the presence of variations due to manufacturing tolerance and slow engine degradation due to "normal" usage. Software logic to be implemented will be available. The challenge will be to integrate the research controls with the "bill of material" control laws to provide a safe override of the adaptive control. Justification for Flight Test: Flight test is required to reduce technology risk and increase acceptance of adaptive control technology. Safe operation of the adaptive control with benefits achieved by optimized performance will make this happen. Current Schedule & TRL: The adaptive control logic is expected to be at TRL 3-4 by FY04. Schedule to Support Flight Testing: An additional \$600K and a 6 month effort will be required to first test technology on engine tests to ensure safe operation under various modes. Flight Test-bed Requirements: The challenge will be to ensure proper communication between bill of material control and the adaptive control logic to ensure safe operation. The flight profile requirement is benign - general cycle of take-off, cruise and landing - about 50 cycles. Success Criteria for Flight Testing: Show that "nominal" engine performance is maintained even as the engine degrades with use.

B.4.2 Model-Based Fault Tolerant Control [18]	C-17 PCHM Working Group POC: Don Simon Technology Description: An advanced form of analytical redundancy consisting of an on-board engine model and an associated tracking filter to “tune” the model to match the performance of the physical engine. The tuned engine model provides 1) Real-time monitoring of component performance, 2) Synthesized estimates of measurable parameters for sensor/actuator fault detection isolation and accommodation, and 3) Synthesized estimates of un-measurable parameters for new control strategies. The focus of this technology is on enhancing safety through the early diagnosis of incipient fault signatures, and in the event of a fault, mitigating its impact via control accommodating action. Justification for Flight Test: Flight test is required to reduce technology risk and increase acceptance of the model-based fault tolerant control technology. Current Schedule & TRL: The adaptive control logic is expected to be at TRL 3-4 by FY06. Schedule to Support Flight Testing: Schedule – To be determined. Risk: Obtaining adequate resources (people & \$), addressing technology proprietary issues, re-designing technology to apply to C-17 F117 engine. Flight Test-bed Requirements: Real-time on-board processing and proper communication between bill of material control and the model-based fault tolerant control logic to ensure safe operation. Success Criteria for Flight Testing: Successful Real-time implementation and operation of control logic. System correctly detects, isolates, and accommodates any actual or simulated engine faults.
B.4.3 Autonomous Propulsion System Technology	C-17 PCHM Working Group POC: Sanjay Garg Technology Description: Seeks to reduce or eliminate human dependency in the control and operation of aircraft propulsion systems. This technology includes a self-diagnostic adaptive engine control system that 1) Performs autonomous propulsion system monitoring, diagnosing, and adapting functions; 2) Combines information from multiple disparate sources using state-of-the-art data fusion technology; and 3) Communicates with vehicle management system and flight control to optimize overall system performance. Such technology supports unmanned air vehicle (UAV) operation and would also enhance the safety of manned vehicles by reducing pilot workload. Justification for Flight Test: Flight test is required to reduce technology risk and increase acceptance of autonomous propulsion control technology. Current Schedule & TRL: The autonomous propulsion control logic is expected to be at TRL 3-4 by FY05. Schedule to Support Flight Testing: An additional \$2M and a 12 month effort will be required to first test technology on engine tests and real-time vehicle flight control hardware integration tests to ensure safe operation under various modes. Flight Test-bed Requirements: The challenge will be to ensure proper communication between bill of material engine control, the vehicle flight control, and the autonomous propulsion control logic to ensure safe operation. Flight profile requirement are TBD. Success Criteria for Flight Testing: Show that "nominal" engine performance is maintained with autonomous propulsion control in use. Also show that autonomous propulsion control is able to recognize and respond to varying engine conditions or changing vehicle flight control requirements.

B.4.4 Propulsion Control for Integration with Intelligent Flight Control	<u>C-17 PCHM Working Group POC:</u> Sanjay Garg <u>Technology Description:</u> There is no current activity. However, ARC has expressed interest in exploring the potential for advanced modes for the propulsion system, such as rapid thrust mode, to enable use of the propulsion system as a primary flight control effector. <u>Justification for Flight Test:</u> Flight test of this technology will be required to demonstrate that the "bandwidth" desired for pilot control of flight is achievable <u>Current Schedule & TRL:</u> No current program. <u>Schedule to Support Flight Testing:</u> Will need to be coordinated with the Intelligent Flight Control effort. <u>Flight Test-bed Requirements:</u> To be determined. <u>Success Criteria for Flight Testing:</u> To be determined.
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